The Ohio State University

Analyzing the Correlation between High Energy Neutrinos and Cosmic Rays

by

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“What I cannot create, I do not understand”

Richard P. Feynman

Abstract

Neutrinos and cosmic rays are highly relativistic particles that pervade the universe and have energies beyond those of man-made experiments. These particles are thought to be produced by some of the most violent astrophysical events in the universe. It is thought that these events, such as supernovae, are capable of producing and accelerating primary particles, such as cosmic rays, to such high energies. When these primary particles interact with the surrounding medium, secondary particles such as neutrinos can be produced with immense energies. An experiment that detects these high-energy particles is IceCube. IceCube is located at the South Pole and has been recording data since 2008. Analyzing data from 2008-2015, it is possible to calculate if there is a correlation between high-energy neutrinos (HEν) and cosmic rays (HECR). Since the HECR seem to be isotropic and random, a window can be placed around a HEν and the amount of HECR that pass through this window can be counted. Comparing these counts to a Monte Carlo simulation can help verify if HEν and HECR are correlated and originate from the same, nearby, astrophysical source.

Acknowledgements

I would like to thank everyone in Dr. Beatty's lab. First, I would like to thank Dr. Beatty for giving me the opportunity to conduct my own research project and providing all around advice throughout my time in his lab. Next, I would like to thank Dr. Michael Sutherland for providing extensive guidance through this project and being available for any and all of my questions. Finally, I would to thank Annie Taylor for her unwavering support throughout my physics degree.

1. Introduction

Neutrinos (ν) are nearly massless electrically neutral spin-$\frac{1}{2}$ leptons while cosmic rays are highly energetic particles that are usually composed of the nuclei of atoms. Charged cosmic rays will be deflected by the galactic magnetic field. As a result, it is hard to trace back to the source where the cosmic ray originated. However, if the cosmic ray has no charge, like a neutron, it will not be deflected by any magnetic fields. Since ν only interact via the weak force and gravity, they also will travel straight from their source. The question remains of where high energy cosmic rays (HECR) and neutrinos (HEν) originate from. The caveat of ν interacting only via the weak interaction is that HEν are hard to detect due to their low probability of interaction. IceCube is an experiment that detects HEν and HECR and is located at the South Pole. It encompasses a cubic kilometer of ice and is composed of two components: IceTop and an in-ice component [1]. IceTop detects HECR while the in-ice component detects HEν. It is possible to analyze the correlation between the number of HECR observed in an angular window centered around a HEν. The motivation for this correlation study comes from the idea that HECR and HEν may be produced by the same, nearby, astrophysical sources. This could also imply a correlation between HEν and neutrons depending on the angular scale of the window. By comparing the observed number of HECR to an expected number of HECR, it is possible to determine if there is a statistically significant correlation . Thus, constructing a model that calculates the number of expected and observed HECR that pass through an angular window for each HEν allows us to investigate a possible correlation between HEν and HECR. If there is any statistical significance found then further studies could be completed to find out why more or less HECR passed through a certain window and if they originate from the same astrophysical source as the HEν.

2. History and Theory of Cosmic Rays, IceCube and Neutrinos

2.1 Cosmic Rays

In 1912, Vector Hess discovered cosmic rays during an experiment in which he ascended to high altitudes in a hot air balloon and found that an electroscope discharged faster as altitude increased; Hess was then awarded the Nobel Prize in 1936 for his work [2]. Cosmic rays (CR) are particles that are mainly composed of atomic nuclei but they can also be electrons or other sub-atomic particles. The majority of the cosmic rays that are detected were produced by a source somewhere in the Milky Way. The two most common elements that make up CR are hydrogen and helium, which account for almost ninety-nine percent of CR [2]. Fig. 1 shows that CR usually have energies that range from 100 MeV to hundreds of EeV; HECR have energies greater than 1 GeV. It is currently thought that HECR are accelerated to such high energies by astrophysical objects such as supernovae, active galactic nuclei and black hole accretion disks

[3]. To date the most energetic particle ever detected was a cosmic ray and had an approximate energy of 300 EeV [4].

Since most cosmic rays are not electrically neutral, they interact with the galactic magnetic field and this results in their trajectory being bent. However, it is possible to reconstruct the arrival direction of the cosmic ray. Since neutrons are electrically neutral their trajectories will not be bent, similar to a ν and this results in the neutrons traveling straight from the astrophysical source. However, the neutron must be above a certain energy threshold to make it to Earth from a nearby astrophysical source. This threshold energy (eqn. 1) can be used to calculate the decay length of a neutron.

$$d = \gamma c \tau \tag{1}$$

In eqn. 1, τ is the lifetime of a free neutron and equals 881.5 seconds. For a 1 PeV neutron, the decay length is approximately 9 pc.

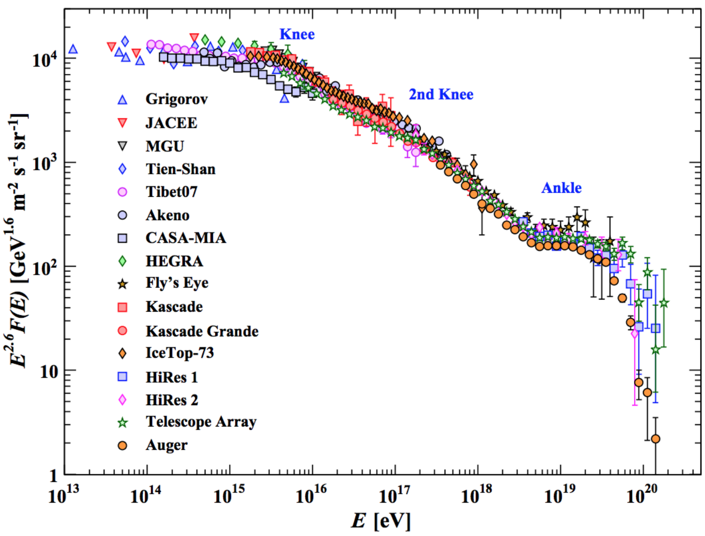

Figure 1: The energy spectrum of cosmic rays that have been detected by various experiments [5].

2.2 Neutrinos - Little Neutral One

Neutrinos were first theorized to exist in 1930 by Wolfgang Pauli while he was studying β-decay. As a function of energy, β-decay forms a continuous distribution and tails off at different values; this seemingly lead to a violation of conservation of energy. However, the existence of a new very light, weakly interacting particle would conserve energy in β-decay. During this time, Enrico Fermi worked out a theory of weak interactions which accurately described radioactive decay as well as predicting that "neutrinos" were produced in these decays. Neutrinos were first detected in 1956 by Clyde Cowan et al.; this result lead to the group of scientists being awarded the 1995 Nobel prize [6]. Neutrinos are neutral, elementary particles that only interact with other particles via the weak nuclear force. There are three flavors of neutrinos, the tau neutrino (ν_τ), the muon neutrino (ν_μ) and the electron neutrino (ν_e); all of which are produced by the decay of radioactive elements and various particle interactions. IceCube is able to detect all three, although it has yet to detect an identifiable ν_τ. The HEν that IceCube aims to detect have energies above 100 TeV; these energies are greater than anything humans have ever produced [7]. It is thought that HEν are produced by astrophysical objects similar to the CR sources and other various potential candidates although none have been experimentally confirmed [8]. The IceCube Neutrino Observatory was able to detect a neutrino flux with energies in the PeV range but was not able to identify individual sources. These neutrinos are the most energetic neutrinos detected to date.

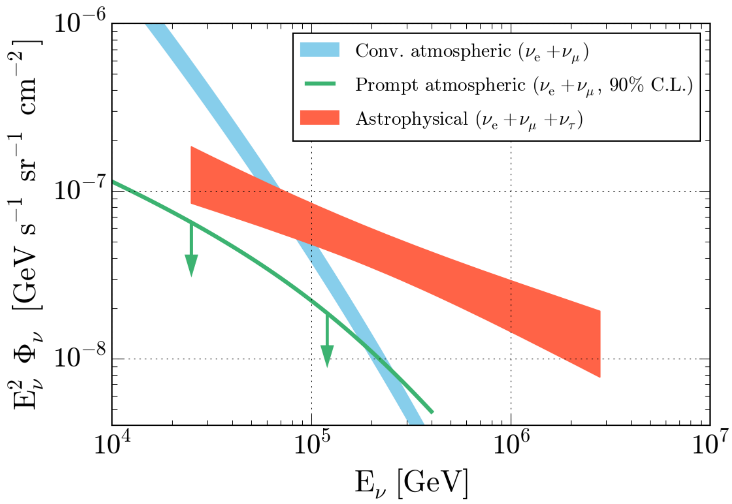

Figure 2: The high energy spectrum of neutrinos that have been detected by IceCube. This shows that astrophysical processes are capable of producing the most energetic neutrinos [9].

2.3 The IceCube Experiment

The IceCube Observatory is the largest neutrino detector in the world and is located at the South Pole. Encompassing a cubic kilometer of ice, IceCube uses two different components in order to detect cosmic rays and neutrinos: IceTop and an in-ice component. The South Pole serves as an excellent location for a ν detector because of minimal anthropogenic noise and the ice is radio transparent. IceTop is a surface detector that consists of 162 tanks of ice and each tank contains two digital optical modules (DOMs) [2, 10]. IceTop mainly detects the particle showers that result from HECR interacting with Earth's atmosphere. When a cosmic ray, such as a neutron, enters Earth's atmosphere, it collides with other particles and will create a shower of secondary particles that can be detected on Earth's surface. The particle showers can lead to multiple insights about the primary particles that created the shower, which are HECR in this case. It allows us to possibly trace back where HECR came from, their energy and other attributes. The in-ice component is the portion of IceCube that is used to detect HEν. The majority of the DOMs used in IceCube are a part of the in-ice component, which uses 5,160 out of the 5,484. Sixty DOMs are attached to a cable that is then lowered deep into the ice; there are 86 cables in total [11]. IceCube detects ν and CR through Cherenkov radiation. When a ν or CR interacts with other particles, secondary charged particles are produced that travel faster than the speed of light in the ice and will produce radiation that can be detected. Each DOM has photomultiplier tubes inside that detect this Cherenkov radiation. By spreading DOMs over a cubic kilometer, it is possible to record the incoming direction, energy and various other characteristics about the ν.

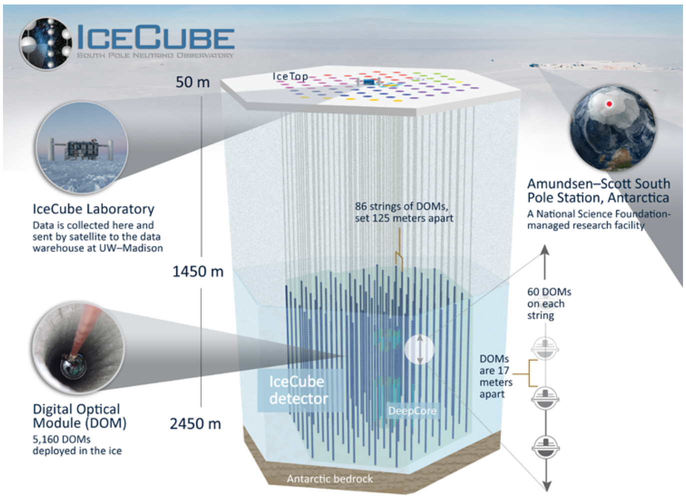

Figure 3: A diagram of the IceCube experiment which shows IceTop and the in-ice component [12].

From 2008-present, IceCube has been operational and collecting data. During this time, IceCube performed a two part search that analyzed the whole sky for HEν and targeted astrophysical objects that were thought to produce these energetic particles. The results of this data lead to multiple groups of different types of potential candidates such as, supernova remnants and radio quasars. Using an unbinned likelihood, the analysis of this data revealed that there was not a significant excess of astrophysical neutrino sources to be found [13]. However during this period of time IceCube detected the most energetic ν ever detected, which had an energy of 4.5 ± 1.2 PeV [13].

3. Methodology

The objective of this correlation study was to analyze seven years of IceCube data by combining HEν and HECR datasets. This data contained information about HEν and HECR such as the declination (δ), right ascension (ϕ), energy, etc. To calculate a correlation between the HEν and HECR, a window was placed around each HEν and then it was counted how many HECR passed through this window. This value was then compared to the average number of counts expected from 2500 Monte Carlo simulations. The windows were constructed with radii that varied from 1 to 25 degrees and were incremented in 1 degree steps. For a specified radius, only δ and ϕ were needed to calculate where the HEν and HECR were located. The values of ϕ range from [0, 360]° and δ ranges from [-90,-53]° . The limited range of δ is due to IceTop not being able to accurately reconstruct events past 37° from the vertical. Since IceCube is located at the South Pole, this declination value is -90° at the vertical; thus, the max declination is -53°. All the ν events with δ greater than -53° were not considered. Also, all HECR with an energy less than 100 PeV were filtered out since we are only interested in high-energy events. After filtering out the appropriate events, a simulation was run for each HEν at a specific radius. A band filter was used to check if a HECR had a δ that was within the window radius (S) of the $\delta_{HE\nu}$. If an HECR passed this check, S was calculated between HEν and HECR. S was calculated using the "great circle distance" equation (eqn. 2).

$$S = \arccos(\sin\delta_{HE\nu}\sin\delta_{HECR} + \cos\delta_{HE\nu}\cos\delta_{HECR}\cos(\phi_{HE\nu} - \phi_{HECR})) \tag{2}$$

If S was less than the specified radius, the HECR was concluded to be in the HEν window and was counted. This process was repeated for all the HECR to see how many fell in a given HEν window. Then using Monte Carlo methods, a randomly generated ϕ was paired with a real δ and given to each HECR event. It was then calculated how many of these Monte Carlo HECR passed through the window. This was repeated 2500 times. The purpose of the Monte Carlo simulation was to show how many HECR we can expect to pass through a window if the HECR are truly random and uncorrelated with the HEν. On large angular scales, the HECR appear anisotropically distributed; a random ϕ makes the HECR appear isotropic allowing us to investigate whether or not the HECR are correlated with HEν. After obtaining all the counts and running the simulation for each S, the Monte Carlo distribution was fit with a Gaussian function and compared to the observed correlation number (correlation number equals the total HECR count in a given window).

The mean and standard deviation were obtained from the Gaussian fit. Thus, the mean value (μ) represents the expected correlation number. It was then calculated how many standard deviations (σ) the observed correlation number (x) fell from μ (eqn. 3).

$$\xi = \frac{x-\mu}{\sigma} \tag{3}$$

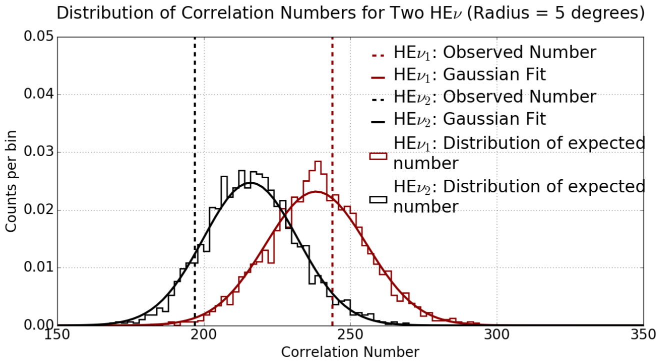

Figure 4: A plot of all 2500 Monte Carlo correlation numbers for two representative HEν events. The dashed line represents the observed correlation number from the data.

For a given window radius, ξ was calculated for the different HEν. Then plotting ξ allows us to investigate if a statistically significant correlation was occurring. Finally, an energy cut was imposed on the HEν in order to look at the fifteen most energetic ν that were detected. An energy cut was imposed because we can be sure that these are all astrophysical HEν and not atmospheric ν. Fig. 2 shows that above a certain energy, only astrophysical processes can produce such energetic ν. This ensures that if a correlation was seen with these HEν, it would possibly have an astrophysical cause.

To check whether or not these results show HECR are correlated with the HEν, a distribution of ξ was made where Monte Carlo data was treated as the real data. This provides a mock data set where we know the distribution that should be expected. Figs. 5-6 provide a check that the HECR are uncorrelated with the HEν.

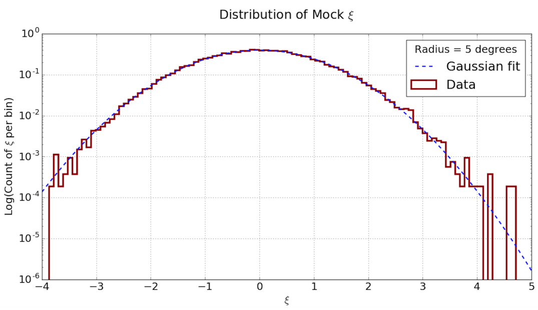

Figure 5: A mock plot of ξ for all 62,258 HEν for a window radius of 5°.

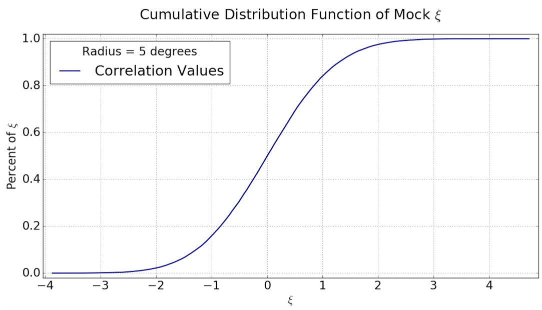

Figure 6: The cumulative distribution function for the distribution in Fig. 5.

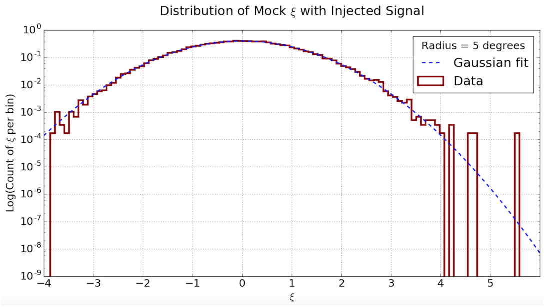

Figure 7: A plot of the artificially injected correlation for a window radius of 5°.

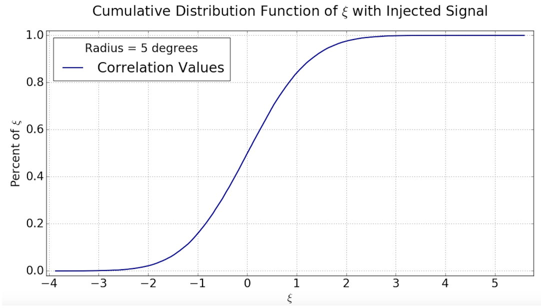

Figure 8: The cumulative distribution function of the distribution in Fig. 7.

Another check that was performed was artificially injecting a positively correlated event into the mock data. Figs. 7-8 show us what a significant positive correlation would look like if one had occurred in with the real data. To obtain Figs. 7-8, an artificial ξ was injected at 5.6σ. In order to inject a signal into the Monte Carlo data, the radius of the 5° window was increased by 1.15° to artificially increase the observed correlation number.

4. Data Results

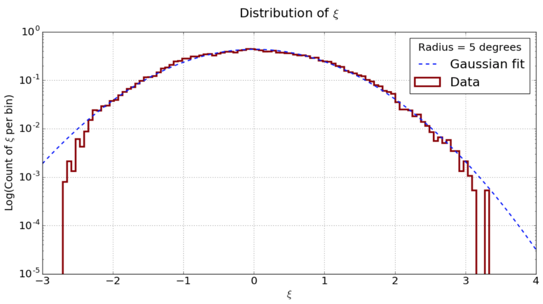

Figure 9: A plot of ξ for all 62,258 HEν for a window radius of 5°.

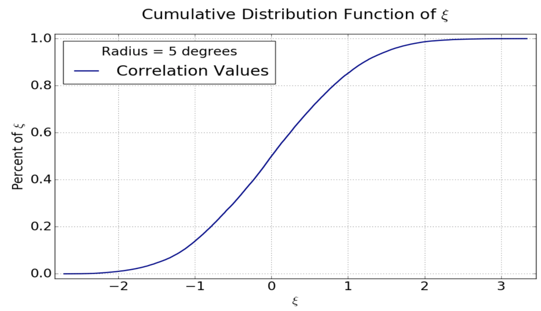

Figure 10: The cumulative distribution function for the distribution in Fig. 9.

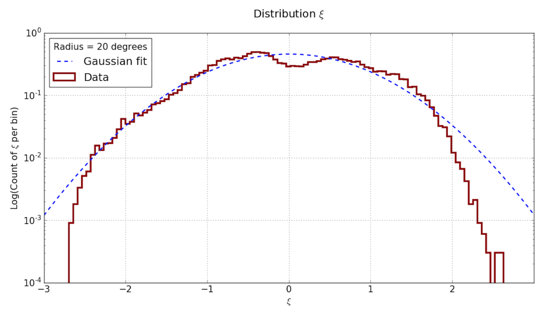

Figure 11: A plot of ξ for all 62,258 HEν for a window radius of 20°.

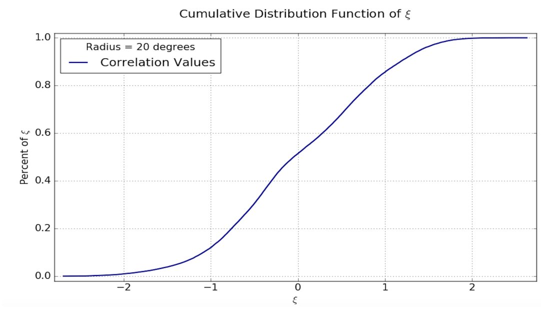

Figure 12: The cumulative distribution function for the distribution in Fig. 11.

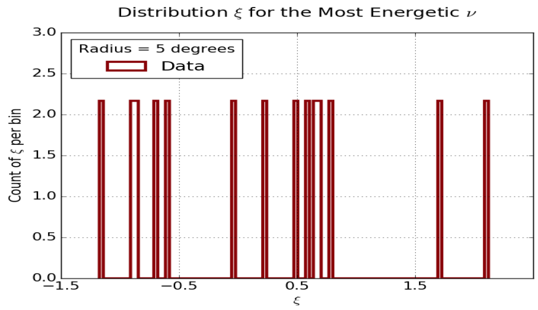

Figure 13: A plot of ξ for the fifteen most energetic neutrinos for a window radius of 5°.

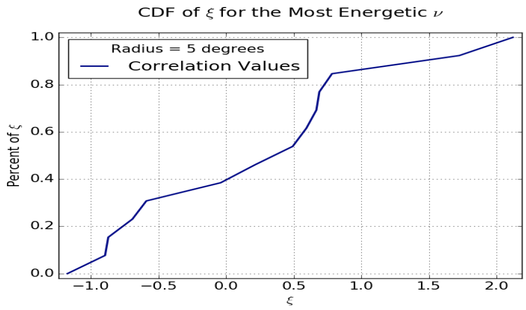

Figure 14: The cumulative distribution function for the distribution in Fig. 13.

The data used in this analysis was recorded from 2008-2015. Figs. 9-12 are representative plots that show the typical results for all the various angular windows (see appendix for similar plots). These plots show that no statistically significant correlation exists. The distribution of ξ followed Gaussian statistics and this shows that the $HE\nu$ were not correlated with the HECR for any S. For $S = 9°$, the data was inconsistent so no results were observed. At large angular scales $S \geq 15°$, the anisotropy of the HECR became evident. Fig. 15 shows the relative intensity of the HECR as a function of δ and ϕ. The two peaks in Fig. 11 are suspected to occur due to the areas of high and low intensity in the cosmic ray arrival directions and because the Monte Carlo simulation treats the HECR as isotropic on all scales. If the Monte Carlo simulation took into account this anisotropy when sampling random directions, it is very reasonable to believe that we would observe a distribution centered around a central peak value. Finally, Figs. 13-14 represent ξ for the fifteen most energetic neutrinos analyzed. Referring to Fig. 2, we can see that the 15 most energetic neutrinos analyzed were produced by an astrophysical source. However, Fig. 13-14 show that there was no statistically significant value of ξ present for these neutrinos. Using a Kolmogorov-Smirnov test, it would be possible to see how probable it is that Figs. 9-10 make up a parent distribution similar to Figs. 13-14 and this would inform us of any statistically significant correlations. Thus, this study suggests that astrophysical HECR and HEν are not correlated.

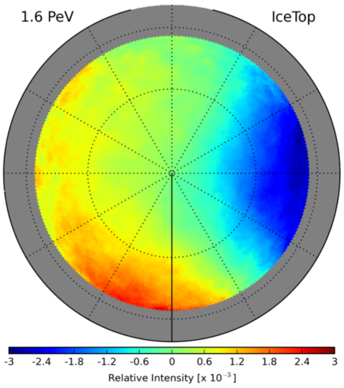

Figure 15: The anisotropic distribution of cosmic rays that have been detected by IceCube [14].

No statistically significant correlations were observed for any HEν at any radii, however, the results of this analysis are still interesting. At small angular scales, the distribution of ξ followed a Gaussian distribution centered around zero. At large angular scales, the distribution split into two peaks. Integrating the area under the curve gives the cumulative distribution function (CDF) which allows us to easily interpret how probable a certain ξ value is for a given window radius. If these plots had resembled Figs. 7-8, a correlation would have been clearly visible in the tails.

5. Conclusions

This analysis found no correlation between HECR and HEν. In the future, other methods could be used to search for a possible correlation. One of these possible methods would be to bin the right ascension values of the HECR. By binning the right ascension values of the HECR, it would be possible to investigate the anisotropic distribution of HECR. This would allow us to determine whether or not a statistically significant correlation occurred at a specific right ascension. Binning the right ascension values along with an energy cut on the HEν would also be a viable option. These various methods could show a correlation between the HECR and HEν or provide evidence that they do not originate from the same astrophysical source.

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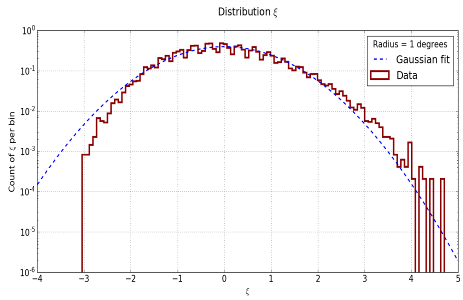
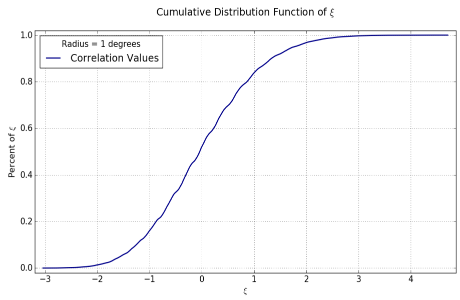
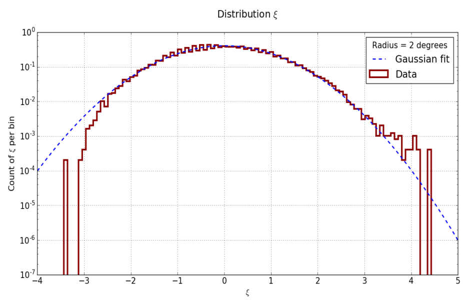
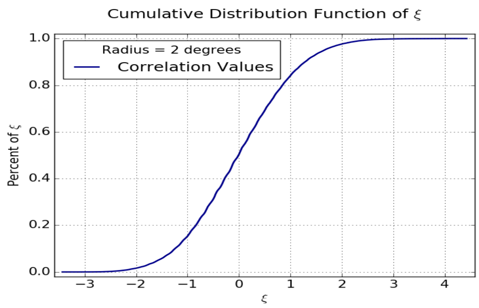
Appendix

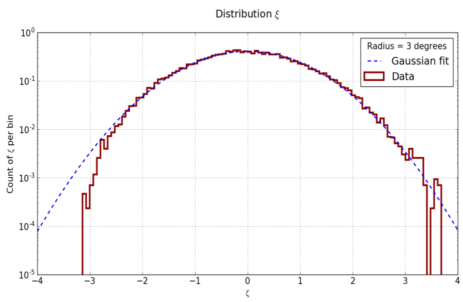
Data Plots and Respective Their CDF

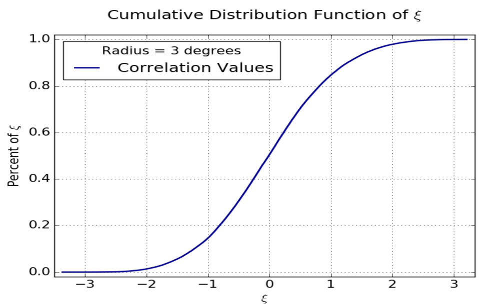


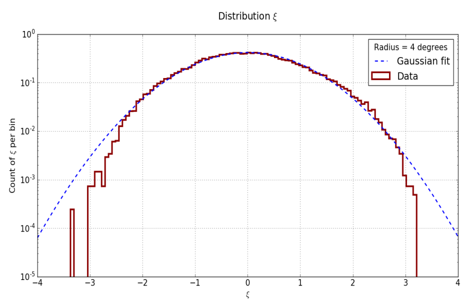


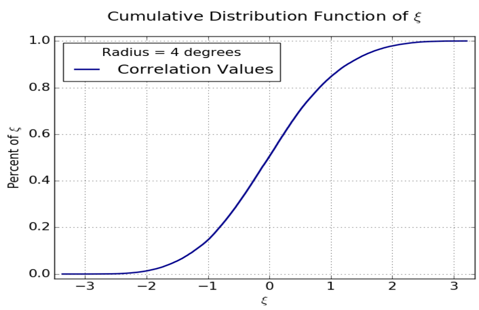


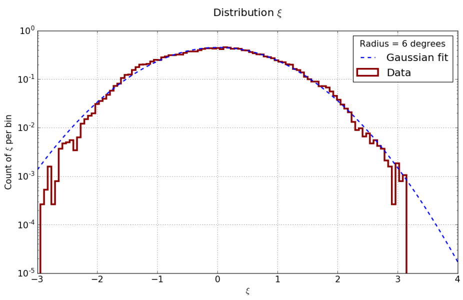




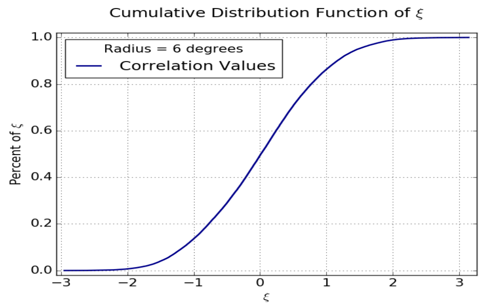




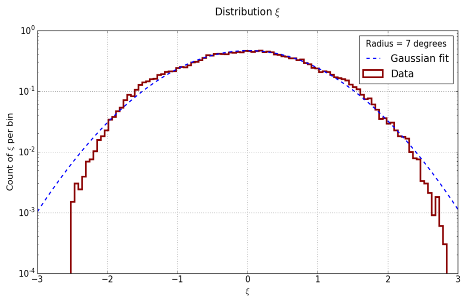




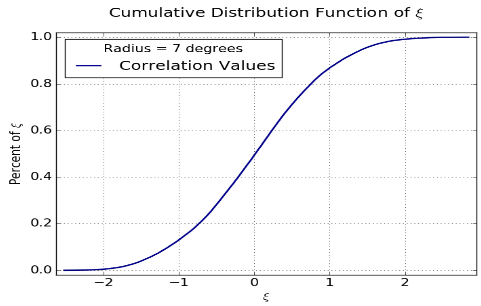
Distribution ξ
Radius = 6 degrees
Gaussian fit
Data
Count of ξ per bin
ξ



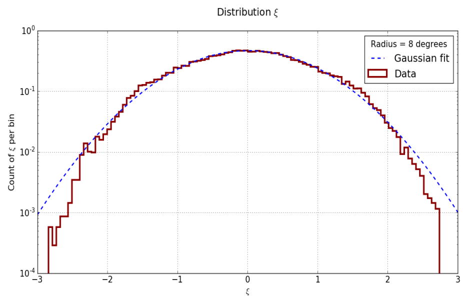
Cumulative Distribution Function of ξ
Radius = 6 degrees
Correlation Values
Percent of ξ
ξ



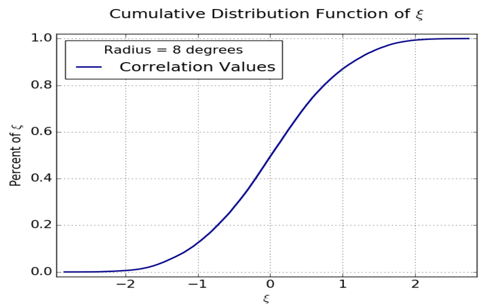
Distribution ξ
Radius = 7 degrees
Gaussian fit
Data
Count of ξ per bin
ξ



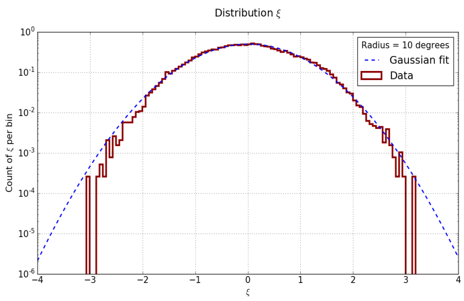
Cumulative Distribution Function of ξ
Radius = 7 degrees
Correlation Values
Percent of ξ
ξ



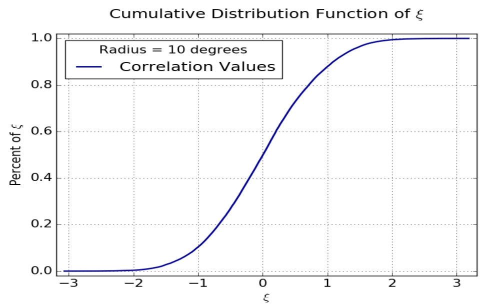
Distribution ξ
Radius = 8 degrees
Gaussian fit
Data
Count of ξ per bin
ξ



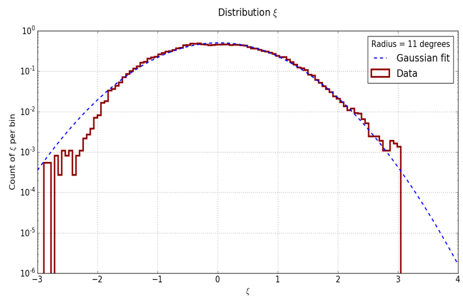
Cumulative Distribution Function of ξ
Radius = 8 degrees
Correlation Values
Percent of ξ
ξ

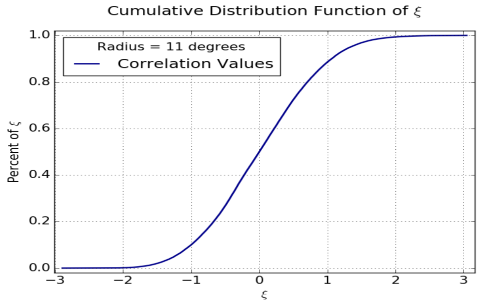


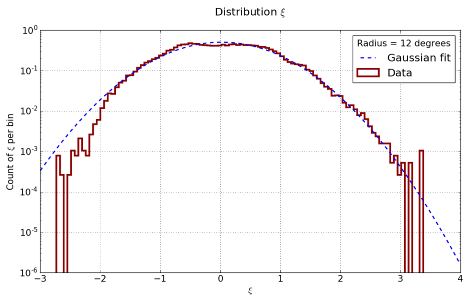
Distribution ξ
Radius = 10 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

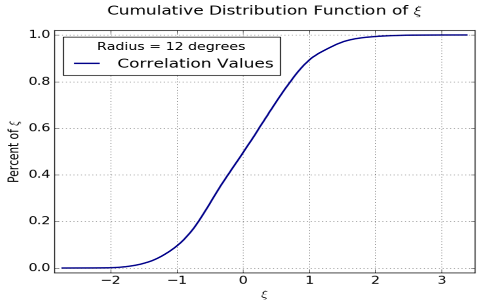


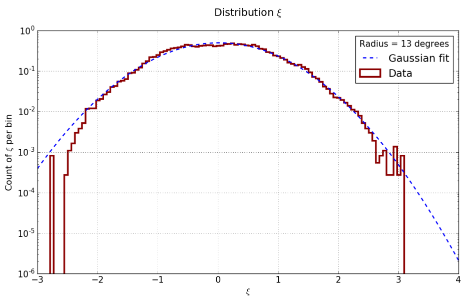
Cumulative Distribution Function of ξ
Radius = 10 degrees
Correlation Values
Percent of ξ
ξ

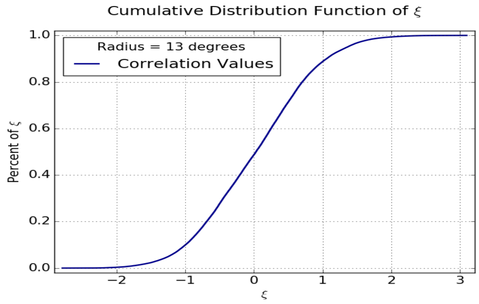

Distribution ξ
Radius = 11 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

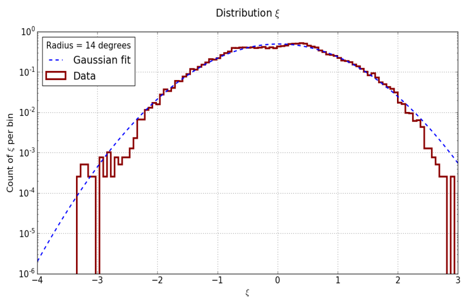

Cumulative Distribution Function of ξ
Radius = 11 degrees
Correlation Values
Percent of ξ
ξ

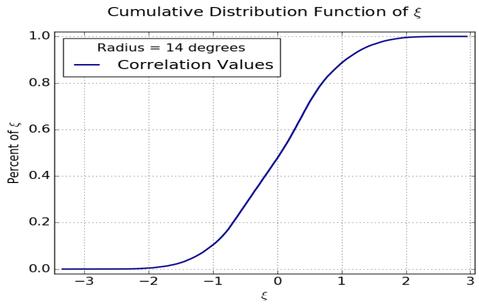

Distribution ξ
Radius = 12 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

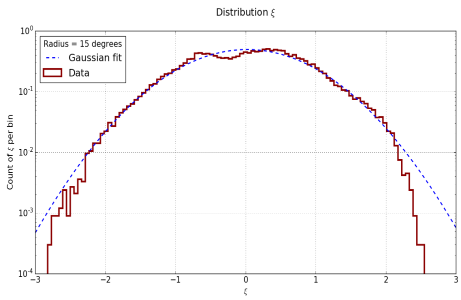

Cumulative Distribution Function of ξ
Radius = 12 degrees
Correlation Values
Percent of ξ
ξ

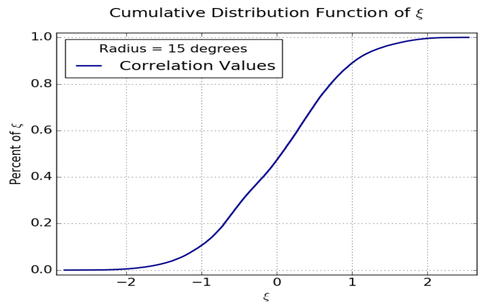

Distribution ξ
Radius = 13 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

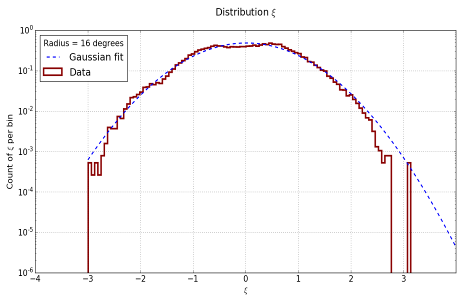

Cumulative Distribution Function of ξ
Radius = 13 degrees
Correlation Values
Percent of ξ
ξ

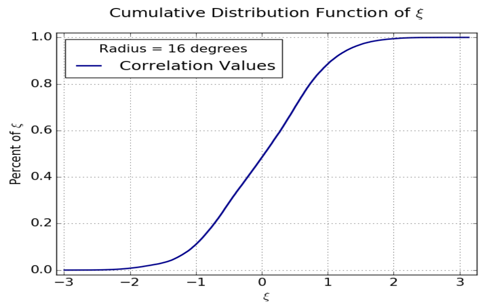

Distribution ξ
Radius = 14 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

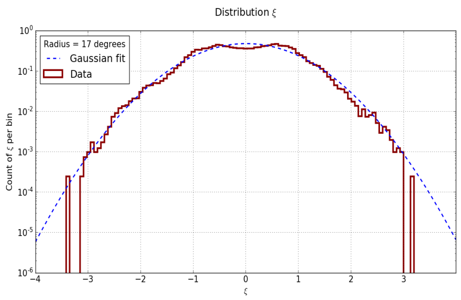

Cumulative Distribution Function of ξ
Radius = 14 degrees
Correlation Values
Percent of ξ
ξ

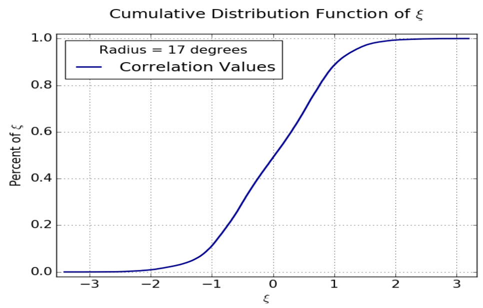

Distribution ξ
Radius = 15 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

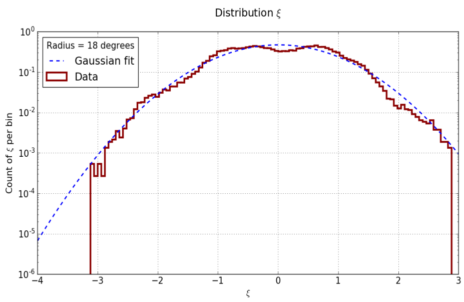

Cumulative Distribution Function of ξ
Radius = 15 degrees
Correlation Values
Percent of ξ
ξ

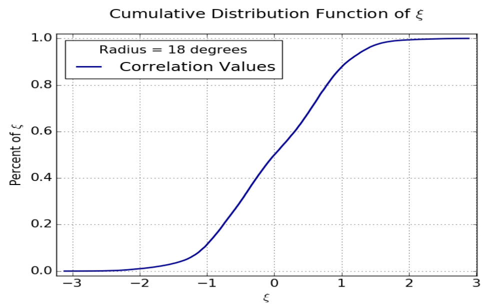

Distribution ξ
Radius = 16 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

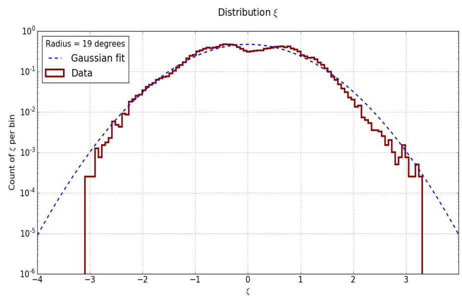

Cumulative Distribution Function of ξ
Radius = 16 degrees
Correlation Values
Percent of ξ
ξ

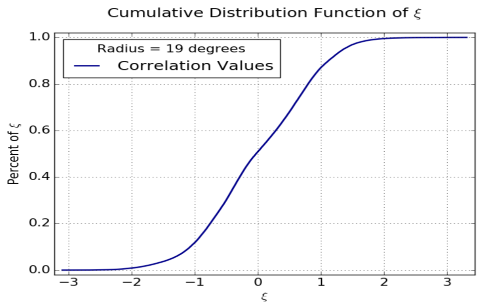

Distribution ξ
Radius = 17 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

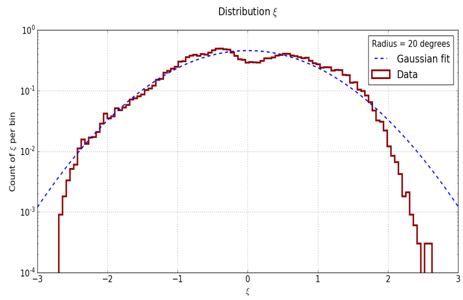

Cumulative Distribution Function of ξ
Radius = 17 degrees
Correlation Values
Percent of ξ
ξ

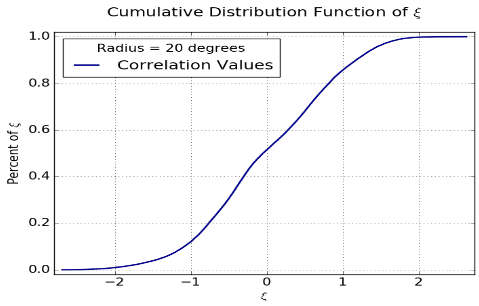

Distribution ξ
Radius = 18 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

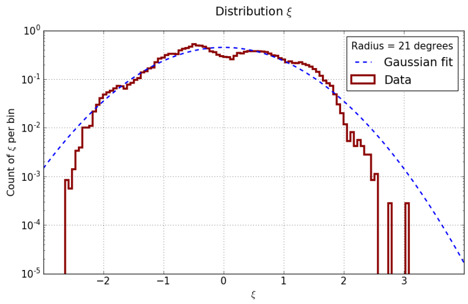

Cumulative Distribution Function of ξ
Radius = 18 degrees
Correlation Values
Percent of ξ
ξ

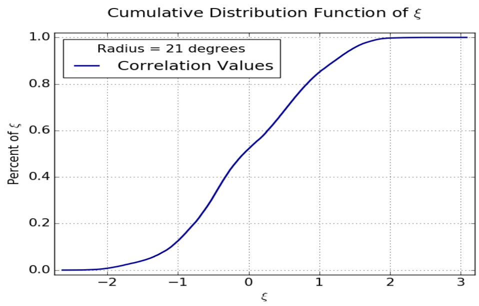

Distribution ξ
Radius = 19 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

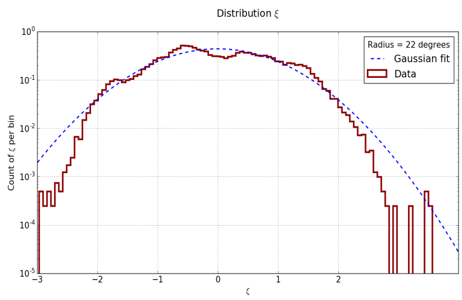

Cumulative Distribution Function of ξ
Radius = 19 degrees
Correlation Values
Percent of ξ
ξ

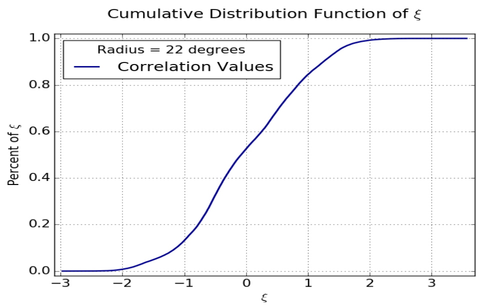

Distribution ξ
Radius = 20 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

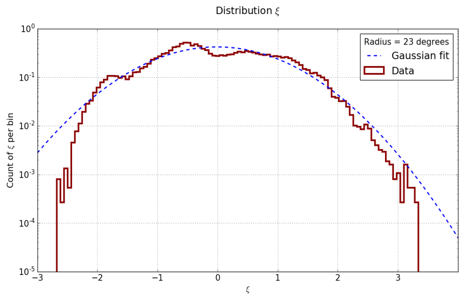

Cumulative Distribution Function of ξ
Radius = 20 degrees
Correlation Values
Percent of ξ
ξ

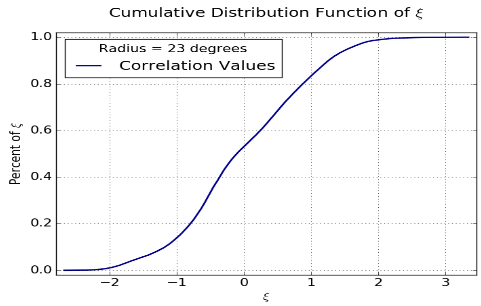

Distribution ξ
Radius = 21 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

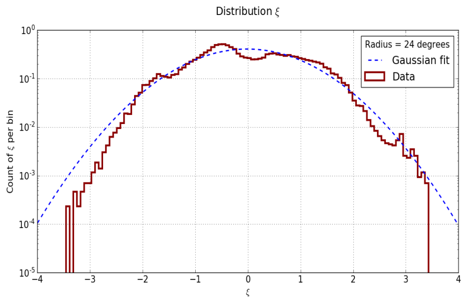

Cumulative Distribution Function of ξ
Radius = 21 degrees
Correlation Values
Percent of ξ
ξ

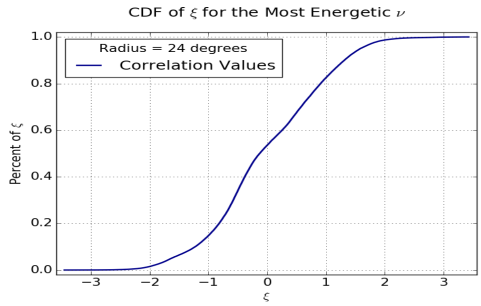

Distribution ξ
Radius = 22 degrees
Gaussian fit
Data
Count of ξ per bin
ξ

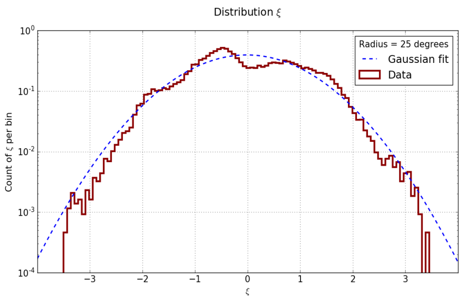

Cumulative Distribution Function of ξ
Radius = 22 degrees
Correlation Values
Percent of ξ
ξ

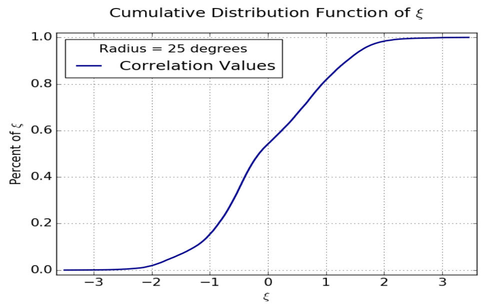




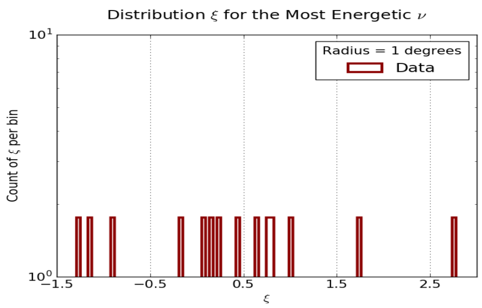


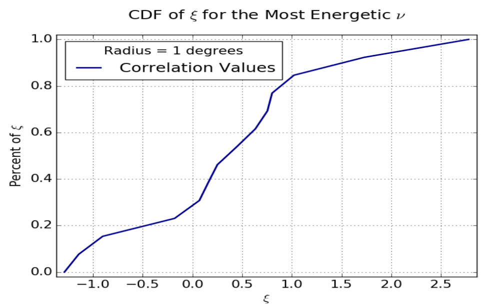


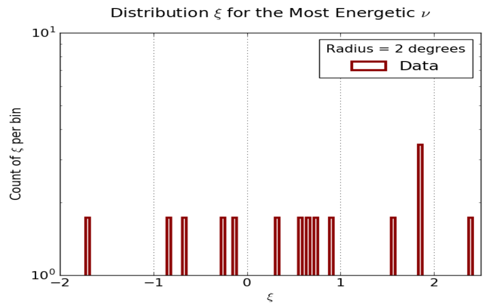


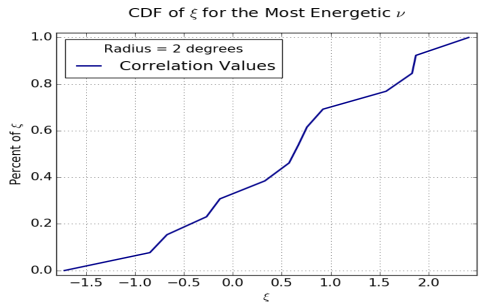


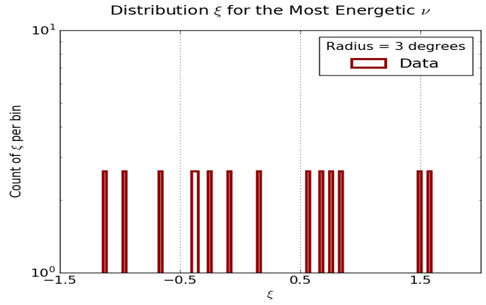
Plots for the Fifteen Most Energetic ν and Their Respective CDF

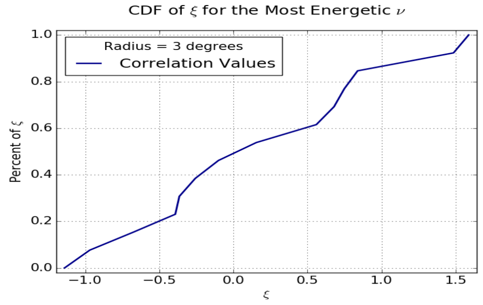


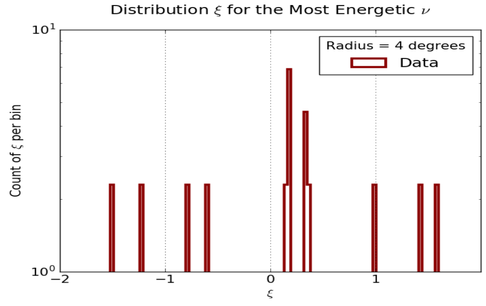


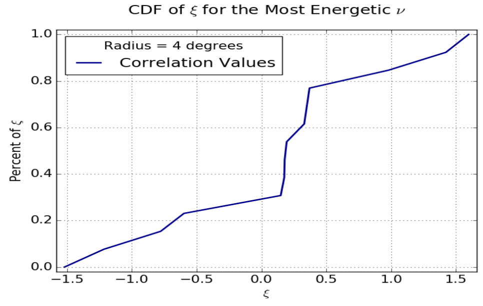

Distribution ξ for the Most Energetic ν
Radius = 2 degrees
Data
Count of ξ per bin
ξ

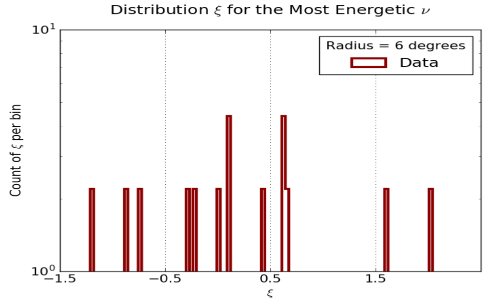

CDF of ξ for the Most Energetic ν
Radius = 2 degrees
Correlation Values
Percent of ξ
ξ

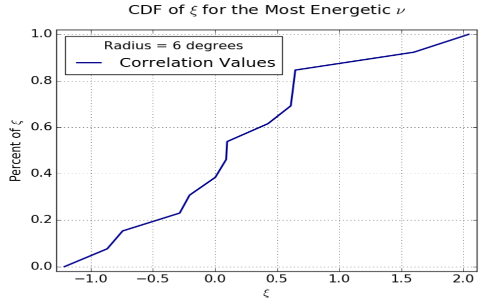

Distribution ξ for the Most Energetic ν
Radius = 3 degrees
Data
Count of ξ per bin
ξ

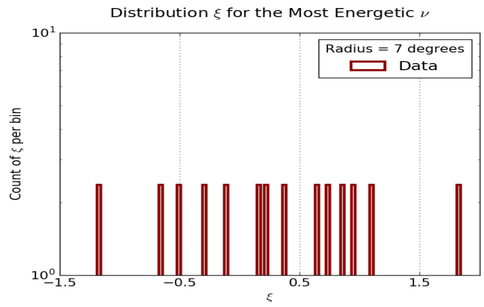

CDF of ξ for the Most Energetic ν
Radius = 3 degrees
Correlation Values
Percent of ξ
ξ

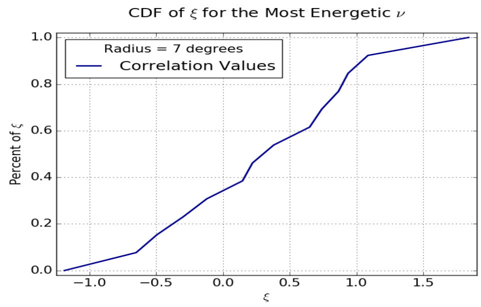

Distribution ξ for the Most Energetic ν
Radius = 4 degrees
Data
Count of ξ per bin
ξ

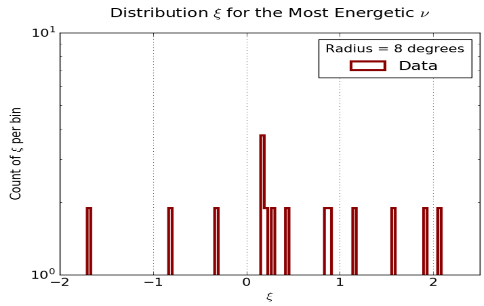

CDF of ξ for the Most Energetic ν
Radius = 4 degrees
Correlation Values
Percent of ξ
ξ

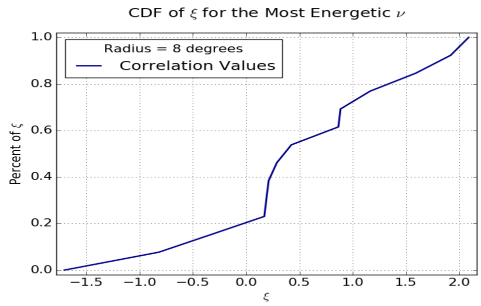

Distribution ξ for the Most Energetic ν
Radius = 6 degrees
Data
Count of ξ per bin
ξ

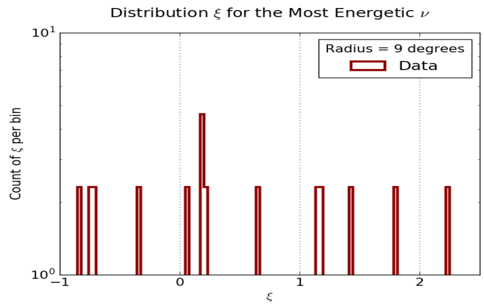

CDF of ξ for the Most Energetic ν
Radius = 6 degrees
Correlation Values
Percent of ξ
ξ

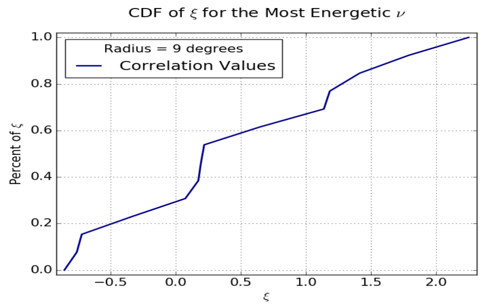

Distribution ξ for the Most Energetic ν
Radius = 7 degrees
Data
Count of ξ per bin
ξ

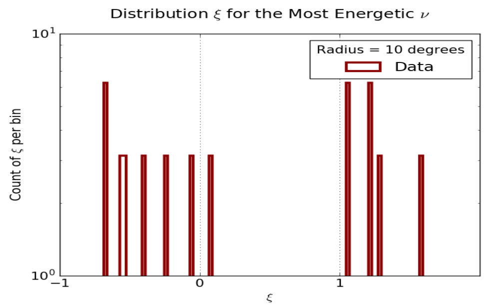

CDF of ξ for the Most Energetic ν
Radius = 7 degrees
Correlation Values
Percent of ξ
ξ

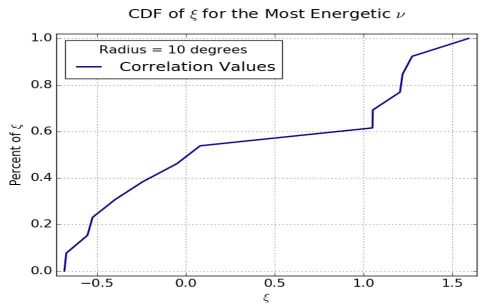

Distribution ξ for the Most Energetic ν
Radius = 8 degrees
Data
Count of ξ per bin
ξ

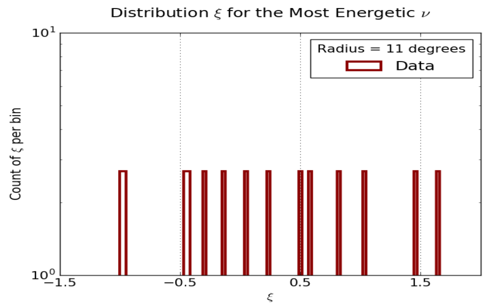

CDF of ξ for the Most Energetic ν
Radius = 8 degrees
Correlation Values
Percent of ξ
ξ

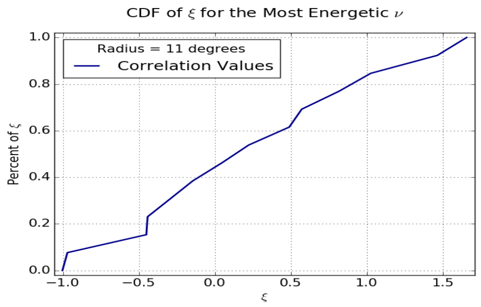

Distribution ξ for the Most Energetic ν
Radius = 9 degrees
Data
Count of ξ per bin
ξ

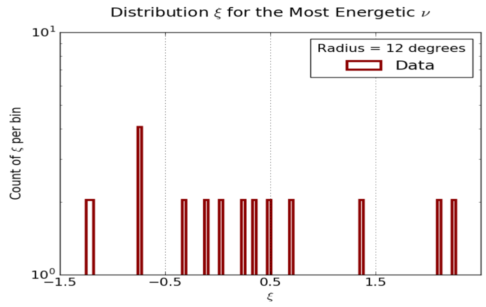

CDF of ξ for the Most Energetic ν
Radius = 9 degrees
Correlation Values
Percent of ξ
ξ

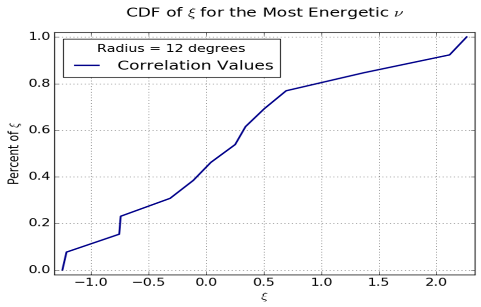

Distribution ξ for the Most Energetic ν
Radius = 10 degrees
Data
Count of ξ per bin
ξ

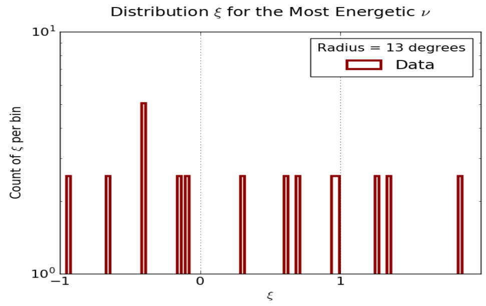

CDF of ξ for the Most Energetic ν
Radius = 10 degrees
Correlation Values
Percent of ξ
ξ

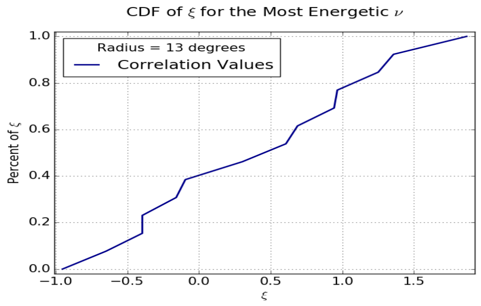

Distribution ξ for the Most Energetic ν
Radius = 11 degrees
Data
Count of ξ per bin
ξ

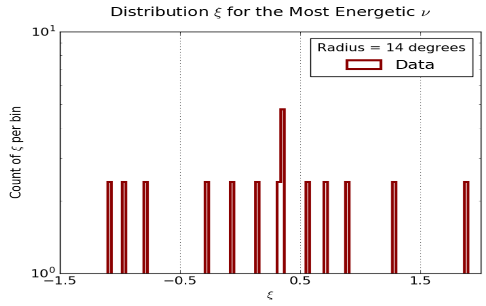

CDF of ξ for the Most Energetic ν
Radius = 11 degrees
Correlation Values
Percent of ξ
ξ

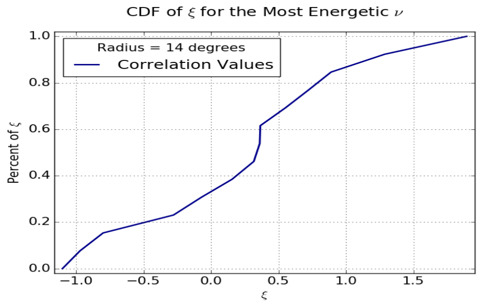

Distribution ξ for the Most Energetic ν
Radius = 12 degrees
Data
Count of ξ per bin
ξ

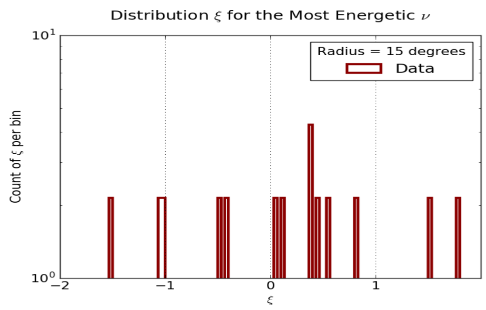

CDF of ξ for the Most Energetic ν
Radius = 12 degrees
Correlation Values
Percent of ξ
ξ

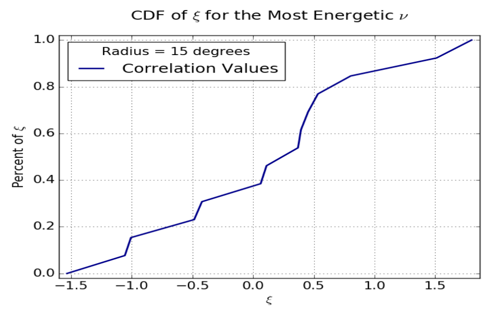

Distribution ξ for the Most Energetic ν
Radius = 13 degrees
Data
Count of ξ per bin
ξ

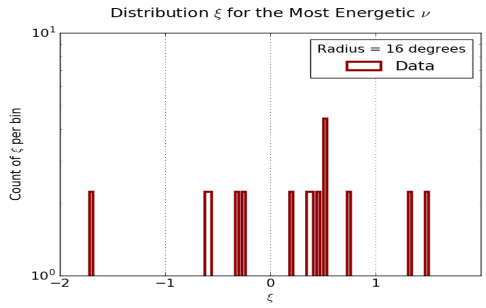

CDF of ξ for the Most Energetic ν
Radius = 13 degrees
Correlation Values
Percent of ξ
ξ

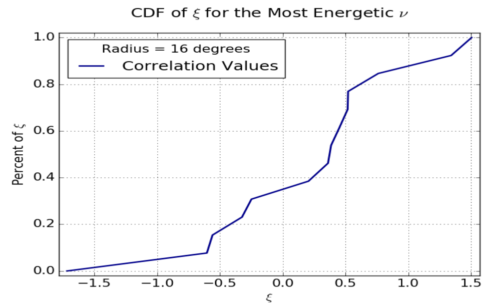

Distribution ξ for the Most Energetic ν
Radius = 14 degrees
Data
Count of ξ per bin
ξ

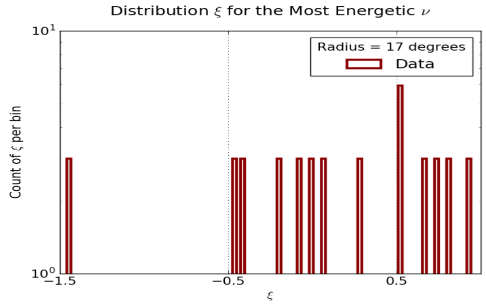

CDF of ξ for the Most Energetic ν
Radius = 14 degrees
Correlation Values
Percent of ξ
ξ

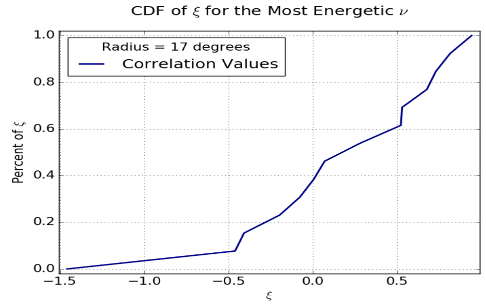

Distribution ξ for the Most Energetic ν
Radius = 15 degrees
Data
Count of ξ per bin
ξ

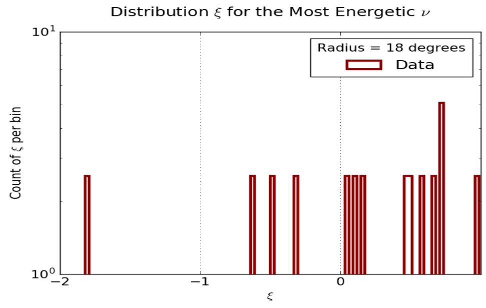

CDF of ξ for the Most Energetic ν
Radius = 15 degrees
Correlation Values
Percent of ξ
ξ

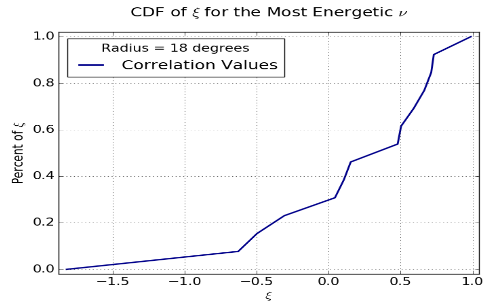

Distribution ξ for the Most Energetic ν
Radius = 16 degrees
Data
Count of ξ per bin
ξ

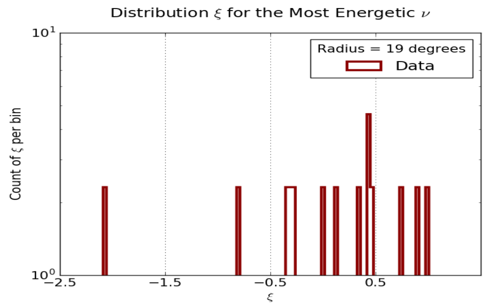

CDF of ξ for the Most Energetic ν
Radius = 16 degrees
Correlation Values
Percent of ξ
ξ

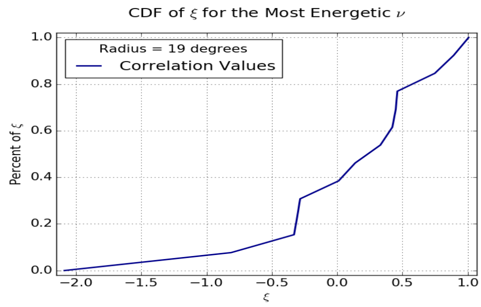

Distribution ξ for the Most Energetic ν
Radius = 17 degrees
Data
Count of ξ per bin
ξ

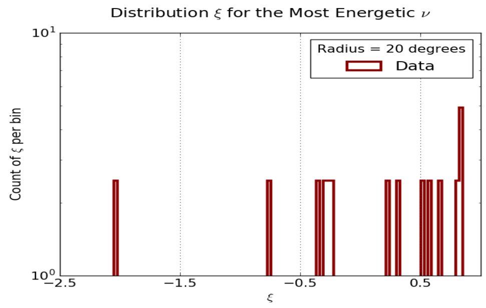

CDF of ξ for the Most Energetic ν
Radius = 17 degrees
Correlation Values
Percent of ξ
ξ

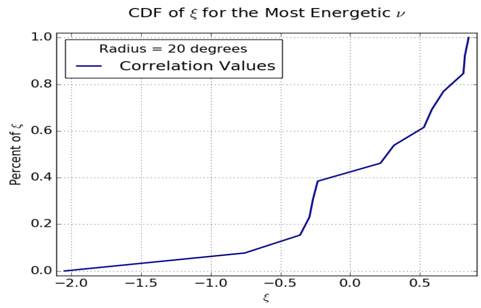

Distribution ξ for the Most Energetic ν
Radius = 18 degrees
Data
Count of ξ per bin
ξ

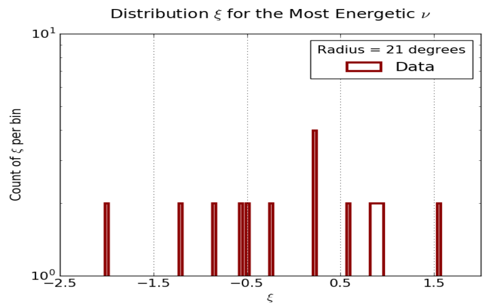

CDF of ξ for the Most Energetic ν
Radius = 18 degrees
Correlation Values
Percent of ξ
ξ

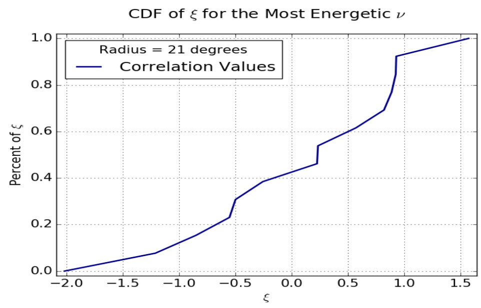

Distribution ξ for the Most Energetic ν
Radius = 19 degrees
Data
Count of ξ per bin
ξ

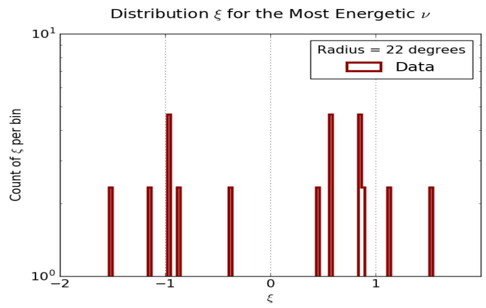

CDF of ξ for the Most Energetic ν
Radius = 19 degrees
Correlation Values
Percent of ξ
ξ

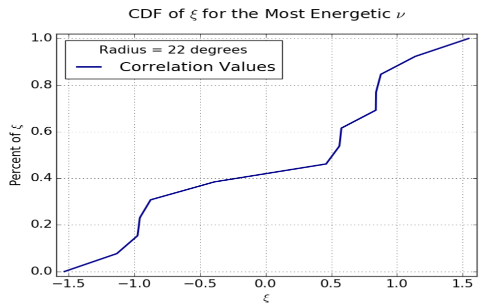

Distribution ξ for the Most Energetic ν
Radius = 20 degrees
Data
Count of ξ per bin
ξ

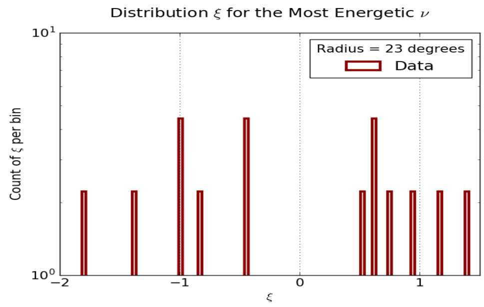

CDF of ξ for the Most Energetic ν
Radius = 20 degrees
Correlation Values
Percent of ξ
ξ

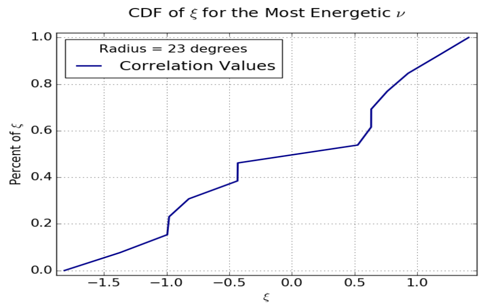

Distribution ξ for the Most Energetic ν
Radius = 21 degrees
Data
Count of ξ per bin
ξ

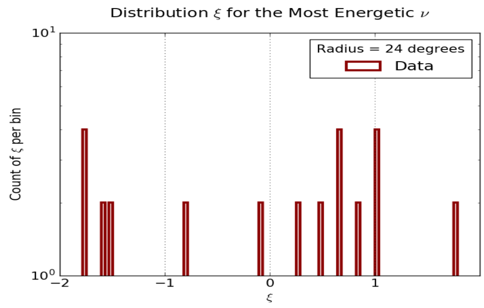

CDF of ξ for the Most Energetic ν
Radius = 21 degrees
Correlation Values
Percent of ξ
ξ

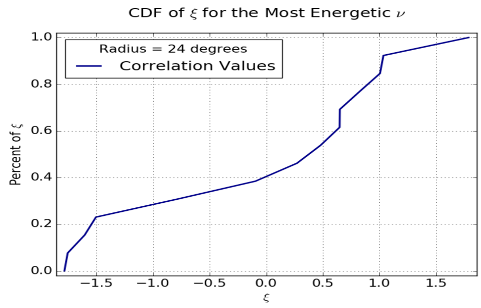

Distribution ξ for the Most Energetic ν
Radius = 22 degrees
Data
Count of ξ per bin
ξ

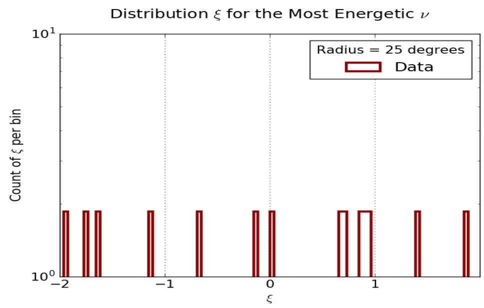

CDF of ξ for the Most Energetic ν
Radius = 22 degrees
Correlation Values
Percent of ξ
ξ

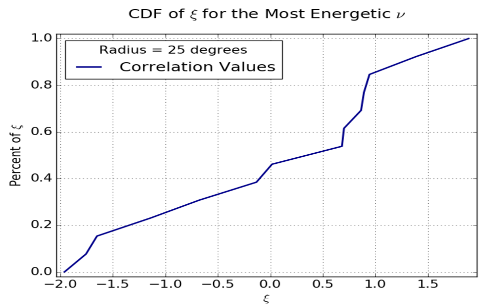

Distribution ξ for the Most Energetic ν
Radius = 23 degrees
Data
Count of ξ per bin
ξ


CDF of ξ for the Most Energetic ν
Radius = 23 degrees
Correlation Values
Percent of ξ
ξ


Distribution ξ for the Most Energetic ν
Radius = 24 degrees
Data
Count of ξ per bin
ξ


CDF of ξ for the Most Energetic ν
Radius = 24 degrees
Correlation Values
Percent of ξ
ξ


Distribution ξ for the Most Energetic ν
Radius = 25 degrees
Data
Count of ξ per bin
ξ


CDF of ξ for the Most Energetic ν
Radius = 25 degrees
Correlation Values
Percent of ξ
ξ